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Energy Performance of a Solar Home Constructed for the Solar Decathlon Competition 2013

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Abstract

Reduction of energy consumption in residential homes is a goal of sustainable construction. The U.S. Department of Energy (DOE) started a biennial Solar Decathlon competition in 2002, in which the students from universities around the globe built energy-efficient and affordable homes suitable for their climate and location. The main goal of this competition was to select the home best designed and built in a sustainable way. This paper describes the home designed and constructed for participation in the 2012-2013 competition by the students at the University of Nevada, Las Vegas. The home was designed for the desert climate of southern Nevada, part of the Mojave Desert. This paper describes the design and construction process of this home, and determines whether it is a net zero energy home.

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Keywords: Energy; Energy Efficiency; Construction, Residential; Net Zero Energy Home; Solar Decathlon

1. Introduction

The United States consumed about 98 quadrillion Btu in 2011, which equals about 19% of the world's total energy consumption [1]; one of the major consumption sectors were residential homes. In 2008, out of 505

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quadrillion Btu of energy consumed worldwide, the residential sector consumed about 18%, making it the third highest among the four major energy end-use sectors: industrial, transportation, residential, and commercial. Residential and commercial buildings consumed about 40% of the total energy in the United States in 2012, which was about 40 quadrillion Btu. Approximately 19% of the electricity generated worldwide is generated from renewable energy sources, which includes hydropower, biomass, biofuels, winds, geothermal, and solar. This is estimated to increase to 23% by 2035 [1].

The newer homes built from 2000 to 2009 consumed only 2% more energy than homes built before 2000, even though many newer homes are 30% larger than the older ones [2]. Due to the use of efficient equipment and improved envelope of the homes, the newer homes consume 21% less energy than the older ones for space heating. On the other hand, 3%, more energy was consumed by new homes for heating, ventilation, and air conditioning (HVAC) appliances, 56% for electronics, and 18% lighting as compared to homes built before 2000. Residential energy consumption from electricity increased in contrast to using natural gas, after being nearly constant for decades. This increase was due to the increase in the number of devices per household. Moreover, the use of other fuels decreased as compared to past energy consumption [2]. In addition, the percentage of central air-conditioning used in homes increased from 45% in 1993 to 60% in 2009.

In 2012, an average of $1,945 per household was spent on heating, cooling, appliances, electronics, and lighting. This accounts for 3.7% of household income, the lowest amount in the recent 10 years [3]. Expenses for energy consumed by such household utilities as water and telephone services, as well as for transportation, were not included in this average. In addition to this, the expenses for energy by U.S. households decreased by $12 billion in 2012 as compared to 2011.

Energy consumption in residential homes has been a subject of interest in research related to sustainability. A study to identify the factors affecting the energy consumption of residential buildings collected data from 30 homes built with Energy Star products, a program of the U.S. Environmental Protection Agency (EPA), and 30 non-Energy-Star homes, all built in 2001, 2005, and 2008 in Henderson, Nevada [4, 5]. Results showed that energy consumption (electricity and natural gas) in residential homes increased with the increase in floor area of these homes. However, homes built in 2008 consumed less electricity than homes built in 2001 and 2005. Homes with double-paned low-e windows saved the most energy compared to homes with single paned and double-paned windows. Also, the energy consumptions were found to increase with the increase in age of the homes as well as with how frequently the air conditioner and washing machine were used. The authors observed that the lower the thermostat temperature was set during the summer, the higher the electricity consumption. Furthermore, the authors observed that the room temperature setting during winter correlated to the mean annual natural-gas consumption per area. Another study was conducted to compare energy consumption of 30 green school buildings (GSBs) and 30 non-green school buildings (NGSBs) of Clark County School District in Nevada. The results showed, on average, the GSBs consumed 32% less energy than NGSBs [6].

Madeja and Moujaes [7] studied the differences in energy consumption in identical homes, except that one set were Zero Energy Homes (ZEHs) having energy-efficient features and the other set were traditionally built homes, used as a baseline. These researchers compared the actual data obtained from these homes with simulation data. The authors observed that the thermal mass used in the ZEHs resulted in a maximum energy consumption of only 25% of the baseline homes when cooling the homes. However, simulation results of the baseline homes showed that Trace 700 simulations overestimated the thermal mass of the structure as compared to actual results. Thus, for cooling, the simulation model estimated 2.25% more energy consumption than what occurred for actual homes; for heating, the simulation model estimated 6% less energy than for actual results. Overall, the simulation results for cooling ZEHs estimated 11% more energy consumption than the homes actually consumed. Moreover, the ZEHs saved 76% energy more than the baseline homes in actuality, which was 1% more than the predicted simulated results.

In another study, it was observed that a ZEH used significantly less electricity than a baseline home [8]. Further, ZEH only consumed electricity during hot weather for four months, from June through September, when the temperature inside the homes needed cool. However, the energy produced from the solar panels of the ZEH was sufficient for the home’s energy needs for the remaining months of the year. Even though the authors encountered problems in the heating systems of the homes during the first year, the ZEH still used more than 50% less energy than the baseline home. The overall energy saved by the ZEH as compared to the baseline home was more than 80%. In addition, the authors calculated the efficiency of the photovoltaic (PV) panel in order to measure its performance.

They observed that during the same four-month period, the efficiency of the PV panels was less when the PV cell temperature and the surrounding temperature were high. The ZEH produced 1700 kWh more energy than required by the home. Taking into consideration all the energy consumed by the home as well as the extra energy consumed due to the plumbing fixture problem, the ZEH still proved to be more energy efficient than the baseline home.

Zhu et al. [9] studied and collected data from a traditional house and a ZEH built in Las Vegas. The wall thickness and overall R-value were 62.5 mm and 2.15 (m^2 ºC)/W, respectively, for the baseline home and 204 mm and 2.06 (m^2 ºC)/W, respectively, for the ZEH. These values were the main components for comparisons of energy consumption. The results showed that the internal wall temperature varied significantly from the external wall temperature in case of the baseline home; with the ZEH, the temperature remained more constant during both the heating and cooling seasons because of its ability to store heat. Furthermore, the overall energy consumption for the mass wall of the ZEH house was less than the baseline house by 14 kWh. The authors concluded that mass walls were able to stabilize the indoor temperature better than conventional walls because they could store heat during the day and release it at night. However, for desert regions, where more sunlight is available, more heat would be stored and released inside the house, increasing the consumption of cooling energy. It was observed that the mass walls reduced the energy consumption, which was advantageous during heating season; however, the energy consumption was comparatively higher for the ZEH than the baseline house during cooling season, which was a disadvantage

2. Solar Decathlon

The Solar Decathlon, a biennial competition organized by U.S. Department of Energy (DOE), first began in 2002. In this competition, the selected teams designed and built energy-efficient, architecturally appealing, and affordable solar-powered homes. The open exhibits during the final week of the competition provided an opportunity to demonstrate and educate the public that these types of homes can be affordable as well as energy-efficient. University of Nevada Las Vegas (UNLV) was selected as one of the 20 teams from around the globe to participate in the Solar Decathlon 2013, held in Irvine, California from October 3 to 13, 2013. The home described in this paper was designed and built by the students of UNLV for this competition with the help of faculty from the School of Architecture and the College of Engineering, including the Construction Management faculty.

The homes in this competition were judged based on 10 factors, each worth a maximum of 100 points for a total of 1,000 points. Architecture, market appeal, engineering, communications, and affordability were juried contests, and comfort zones, hot water, appliances, and the energy balance were measured contests. Moreover, home entertainment was measured in a juried contest.

The engineering contest included the functionality, efficiency, creativity, and reliability of the HVAC system used in the home. The energy balance contest measured the electricity generated and consumed by the home during the entire competition period. For this contest, the home had to generate as much electricity as it consumed. During comfort-zone contest, the teams had to maintain the indoor temperature between 71ºF (22.2ºC) and 76ºF (24.4ºC), and the relative humidity had to be less than 60%. For the hot-water contest, the water system in the home needed to be able to deliver 15 gallons (56.8 L) of hot water at a temperature of 110ºF (43.4ºC) in 10 minutes or less. The temperature of the refrigerator and freezer needed to be within a certain range, and the dishwasher, washer, and dryer needed to operate properly.

Because of these specific competition requirements, UNLV students focused on designing and constructing the insulation of the home, its envelope, the HVAC system, the hot water system, and appliances in such a way that the energy consumption of the entire home could be reduced. The solar panel was designed in such a way that the energy produced by the panel was enough to run the entire home. The home was designed with PV panels and solar thermal collectors for the generation of power.

The objectives of this paper are to discuss the design features of energy-efficient home built for Solar Decathlon Team of UNLV as well as the performance of the home during the competition period.

3. Home Construction and Features

The home designed and constructed by the UNLV team for Solar Decathlon was a single-story, 802-sqft home intended as a vacation home in a semi-arid desert region, specifically, the Mojave Desert of southern Nevada. Called DesertSol, the home was built in two modules connected by a bridge. The two modules could be easily separated, transported, and assembled. The bridge separated the two modules, Module A (west side) and Module B (east side) into the private and public spaces, respectively, of the home. The bedroom, laundry, bathroom, and the mechanical room were located in Module A. The reconfigurable living space was in Module B, and could be used for cooking, dining, and entertaining. The water feature between the two modules on the north side of the bridge provided an opportunity for evaporative cooling, rainwater collection, and gray-water filtration.

3.1. Structural System and Shade Screen System

A hybrid wood-and-steel structural system was designed for this home. The steel members formed a box frame with moment connections and lateral bracing. This was designed to provide enough stability for the structure during transportation as well as during potential seismic events. In order to reduce the thermal bridging, or the transfer of heat between the interior and the exterior of the house, wood studs were used to frame the wall. Moreover, to adapt to the hot dry climate of a semi-arid desert, a ventilated reclaimed wood 'rainscreen' was used to shade the building from the sun and to allow heat to escape during the night. The digitally fabricated screens for this rainscreen were designed to provide shade in the summer; during the winter, the screens could retract to warm the space passively with direct sun.

From an architectural point of view, small holes were cut into the steel screen panels forming an image of a mesquite tree, evocative of the southern Nevada landscape. On the other hand, from the engineering point of view, the screens could act as an enclosure for the home during summer, providing shading for both the patio space and the home's interior. During the day, the screens provide shading; at night, they allow the heat to escape. During winter, the screens could be opened to allow the sun to penetrate into the building and heat it, ultimately reducing the energy consumption of the home.

3.2. Exterior and Interior Walls

Between the 2x6-ft framing in the exterior walls, 1-in closed-cell spray-foam insulation was applied on the exterior side, having a thermal resistance of R 6.7; 4.5-in open-cell spray-foam insulation was applied on the interior side, having a thermal resistance of R 16.65. The spray foam was covered with 3/8-in-thick plywood sheathing on the exterior side of the home. On the exterior, the entire home was wrapped by Tyvek® Stuccowrap for a protection barrier against air and moisture. One-inch foil-faced rigid-foam insulation was placed on top of this wrap in between the furring strips, and was held in place by 7/8-in hat channels at 16-in on center. These hat channels provided the proper air flow on the wall surface. The weathered wood rainscreen was used as a finishing layer on the exterior.

In the interior, 5/8-in type 'X' gypsum board with a level 5 painted finish was installed. This gypsum board was covered with finished wood. The overall R-value of the exterior wall after spraying was 23.4. The interior wall was based on the 2x6-ft framing with spray foam insulation in it. The insulation was covered with 5/8-in-thick type 'X' gypsum board painted on either side. The gypsum board was covered on both sides with the finish material, as designed.

3.3. Roofing and Flooring Systems

The roof of the home was insulated with 1-in closed-cell spray-foam insulation with a thermal resistance of R 6.7 on the exterior side, and 11-in open-cell spray-foam insulation with a thermal resistance of R 40.7 on the interior side. The spray foam insulation was sandwiched between the 3/8-in plywood on the exterior and the 5/8-in type 'X' gypsum board with a level 1 primed finish on the interior. A waterproofing membrane covered the plywood on the exterior. One-inch rigid insulation was placed on top of the waterproofing membrane, on which the standing seam (a metal-finished roof) rested. The overall R-value of the ceiling area after spraying the insulation was R 47.4.

The finished floor was the topmost interior surface of the several layers of the floor. 1/8-in plywood sheathing underneath the finished floor covered the 5/8-in sub-floor. The 5/8-in subfloor rested on the 1-1/8-in structural sub-floor that was laid on the steel chassis. The hollow space made by the C-channel of the steel chassis was filled with insulation: 1-inch closed-cell spray-foam insulation with a thermal resistance of R 6.7 covered by a 9-in open-cell spray-foam insulation below the chassis, having a thermal resistance of R 33.3. The total R-value of this insulation was R 40. For fire resistance, an ignition barrier spray (No-Burn® plus XD) was applied at 3 mils over the open-cell spray-foam insulation. The underside of the whole chassis was covered with a bottom board to provide moisture protection.

3.4. Doors, Windows, and Glazing

Nanawall®, a product qualified by Energy Star, was used for all the operable windows in the home, which created cross ventilation, as well as the exterior doors [10]. In compliance with the 2010 Energy Star qualification, the product needed to have a U-factor that was less than or equal to 0.32 and a solar heat-gain coefficient (SHGC) less than or equal to 0.30 for doors in all climate zones. The windows had a total opening area of approximately 62 sqft. These doors and windows used double-glazed low-E glazing that was insulated and filled with tempered argon; the glazing had a warm edge spacer, and the frames were clear anodized aluminum.

The Nanawall doors of the living room, bedroom, and foyer were mounted on the floor with stainless steel rollers. For the doors, U-factor for the center of glass was 0.26, with a glass thickness of 15/16 in. In addition, the SHGC for the doors was 0.23. The doors and windows sills were sealed with the Tyvek Stuccowrap for moisture protection and air infiltration. To protect against water penetration, flashing tape was used at the window sills to adhere the Tyvek. Low-expanding insulation foam was used in the small openings and holes in the jambs of the doors and windows.

To control the amount of daylight entering the home, glazing was provided more on the south and north sides of the home, and minimum glazing was provided on the east and west sides. The total area of glazing provided in the clerestory windows on the north and west sides of Module B were approximately 61 sqft. The clerestory windows were placed high inside the home to provide enough lighting in all the corners of the home. This helped reduce the energy consumption by reducing the use of electric lights.

3.5. Air Conditioning System

A ductless mini-split heating system was installed to heat or cool the home. Two Mitsubishi MSZ-FE09NA indoor units and two Mitsubishi MUZ-FE09NA outdoor units were installed separately in the two modules. The first indoor unit was installed on the west wall at the northwest corner of Module A, and the second unit was installed on the east wall at the northeast corner of Module B. The outdoor units were installed on ground-mounted equipment pads, away from the decks and the access walkways; they were protected by well-ventilated protective barriers. Both the indoor and outdoor units had a rated capacity for cooling and heating of 9,000 Btu/h (2.64 kW) and 10,900 Btu/h (3.2 kW), respectively [11].

This system used an environmentally friendly R410A refrigerant to reduce the impact on the ozone layer. Usually, a ducted air-conditioning system has a Seasonal Energy Efficiency Ratio (SEER) value of 18, and a conventional system has a SEER value of 15. Both the indoor unit and the outdoor unit used in this home had SEER values of 26. Moreover, a conventional air-conditioning system provides 90% of heat energy and the rest for light energy; however, heat pumps can provide up to three times more heat energy for purpose of air conditioning. This is because in a heat pump, there is no conversion of energy, only movement of energy from the interior of the home to the exterior, and vice-versa.

The main advantage of having two separate units was to allow one unit to be shut off when the space was unoccupied or when the space did not require air conditioning. Therefore, energy was used only when required. In case of failure of one unit, there was a second unit to provide backup for maintaining comfort until the failed unit was repaired. The other main advantage of this ductless system was that it reduced the chances of leakage of the conditioned air into unconditioned spaces. The conditioned air was used directly in the space where it was required without any chance of leakage.

3.6. Ventilation Systems

A Panasonic FV04VE1 Energy Recovery Ventilator (ERV) was installed on the ceiling of the hallway to exchange the fresh air from the outdoor to the interior of the home; this system was connected to the home automation system. The ERV used the temperature and the humidity of the exhaust air and transferred heat as well as moisture to the incoming air to match the temperature and the humidity of the home's interior. However, the incoming air and the exhaust air did not mix. One of the two 4-in ducts supplied fresh outdoor air into the home from the east wall on the northeast side of Module A. The other 4-in duct exhausted stale indoor air to the outside from the east wall right above the foyer ceiling. The minimum distance of 10 ft between these two ducts that was recommended by the manufacturer was maintained.

Besides the indoor air quality, the ERV balanced the air pressure within the home by replacing the exhaust air with fresh outdoor air [12]. The ERV helped reduce heating and cooling loads by helping to maintain the indoor air quality. Using an ERV reduced the total energy consumed by the home because it reduced the total load in the air-conditioning system.

3.7. Photovoltaic System and Solar Thermal Collector System

Thirty SunPower SPR-225-BLK-U solar panels, capable of producing a total of 6.75 kW power, were installed on the standing seam metal roof of both modules; 21 were installed on Module B and 9 were installed on Module A. The angle of tilt of the PV panels was 11º. In addition, a solar thermal collector system was used to heat the water for domestic water and radiant heating. The solar thermal collectors were installed at the southwest side of the house in front of the bedroom, and inclined at an angle of 51º. The collectors provided energy to heat the water in the hot-water storage tank. The lower heat exchanging coil in this storage tank utilized the energy from the solar thermal collectors to heat water in the tank. The upper heat-exchanging coil heated the water for the radiant floor.

3.8. Radiant Floor Heating System

The radiant floor heating system was designed to use the solar thermal energy collected by means of the evacuated tubes in order to heat the home. The system was designed such that when there was sufficient heat energy in the solar thermal storage tank, the radiant floor heating first operated to heat the home's interior. When there was insufficient heat in the solar thermal storage tank due to cloudy weather or cold nights, the control system allowed the mini-split units to operate in the heating mode. These mini-split heat pumps provided redundancy in the system in case of any problem in the solar thermal system or during any long periods of cloudy days. The radiant floor heating was used to heat a 546-sqft area that included 350 sqft of living area, 154 sqft of bedroom area, and 42 sqft of bathroom area. A total of four loops ran all over the home, except in the mechanical room. Two loops in Module B covered the entire living area; in Module A, one loop covered the bedroom area and the other loop covered the bathroom area.

For heating purposes, routes for the conduits of radiant-floor heating were designed. Uponor ½-in hePEX tubing was snapped into the channel of the 4-in-wide Uponor Joist Trak Heat-Transfer Panel along pre-fixed routes. The tubing was placed at a distance of 8 in on center. The ideally stratified hot-water storage tank, installed in the mechanical room, was used to heat the water running through the tubes for radiant floor heating. However, the water in the tank did not circulate through the conduit of the radiant floor heating.

The temperature of the hot water going into the loop was maintained at 90 ºF. In addition to its path back to the hot water tank, the cold water returning from the other end of the loop was connected to a 1-in three-way tempering valve set at 90 ºF. Thus, if the temperature of the water in the loop exceeded 90 ºF before entering into the home, the valve opened to allow the returning cold water to mix with the hot water so that the temperature remained constant.

The only electricity-consuming component in this radiant-floor heating system was the pump that circulated the hot water from the tank to the four loops in the home. The Taco 110 Series-Model 112 pump was used that had ¾-in flanges and a capacity of 1 gpm at the rate of 1 ft of water. The system collected solar energy, which was used to heat the entire home. Offsetting all the energy used made the whole system more energy efficient than other heating mechanisms.

3.9. Appliances

The type of the appliances being used in any home makes a significant difference in the energy consumed by the home. All appliances used in this home were manufactured by Bosch. The built-in refrigerator, the dishwasher, and the washing machine were Energy-Star-qualified products [13]. The yearly electricity used and the yearly operating cost by the refrigerator was estimated to be around 388 kWh and $41, respectively. The cost range of similar models varied from $48 to $58. The estimated operating cost of the Bosch products was based on the national average electricity cost in 2007, which was10.65 cents per kWh, and a natural gas cost of $1.218 per therm. However, this electricity consumption claimed by the manufacturer depended on the utility rates and the expected use by the users or the consumers.

Bosch claims that their dishwasher exceeds Energy Star requirements for water by 68%. The estimated energy consumption by this product was 259 kWh/yr. The estimated yearly operating cost of the dishwasher was $27 when used with an electric water heater and $22 when used with a natural gas water heater. The yearly operating cost of other similar models ranged from $20 to $50. Similarly, the washing machine used in the home exceeded Energy Star requirements by up to 63%. The manufacturer’s estimated energy consumption, based on four wash loads a week, was 140 kWh/yr and the water consumption was 3,904 gal/yr. The estimated yearly operating cost when used with an electric water heater was $15. This estimated yearly operating cost lay in the lower cost range as compared to similar models, which varied from $10 to $71. When used with a natural gas water heater, the estimated yearly operating cost was $12.

The ceiling fans used in the bedroom and the living room, manufactured by Big Ass Fans, were Energy Star products. These fans can be 80% more energy efficient than conventional fans [14]. The company claimed that the fans used only 2 to 30 W of electricity, which is less than 50% of the energy consumed by an average Energy Star residential home. In addition, the company claimed that the annual estimated energy consumption by this product was 50 kWh, with a yearly operating cost of around $5.

4. Cost of Home

In the affordability contest, the homes were judged based on their costs. Teams got a full 100 points if the cost of their home was $250,000 or less and zero points if the cost was $600,000 or more. The initial estimate of this home showed that it would cost about $373,000, including 5% design and pricing contingencies. The subcontractor overhead and profit were included within the rates. The final construction cost of the home was $298,629 with the same markups and contingencies.

5. Performance of the Home

The Solar Decathlon 2013 rules required that some specific tasks needed to be performed for all the measured contests. For this contest, the home had to generate as much electricity as it consumed. In the comfort zone contest, the teams had to maintain the indoor temperature between 71ºF (22.2ºC) and 76ºF (24.4ºC); the relative humidity had to be less than 60%. For the hot water contest, the water system in the home needed to be able to deliver 15 gallons (56.8 L) of hot water having a temperature of 110ºF (43.4ºC) in 10 min or less. The temperature of the refrigerator and freezer needed to be within a range of 34.0ºF (1.11ºC) to 40.0ºF (4.44ºC) and -20.0ºF (-28.9ºC) to 5ºF (-15ºC), respectively; the dishwasher, washer, and dryer needed to operate properly. The tasks required in these contests were designed to resemble activities that would be performed in a typical home. The energy consumption data of the house in this study were based on these requirements of the contest and tasks performed during the contest. The contest period during which the data for this study was collected started from 11:00 a.m. October 3, 2013 to 11:00 a.m. October 11, 2013.

From the data of the Department of Energy, obtained during the actual competition period, a net energy of 0.18 kWh/ft^2 was produced during the competition. The actual energy produced by the home solar system was 0.43 kWh/ft^2, whereas the energy consumed was recorded as 0.25 kWh/ft^2. This demonstrated that DesertSol was a net zero energy house, which meant that DesertSol produced more energy during the competition period than it required. UNLV took second place in the overall competition behind the Vienna University of Technology.

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